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The Nucleus, First Part

By KARL K. DARROW

This article, like its forerunners on radioactivity and transmutation, is devoted to the beginnings of the oncoming stage of atomic physics: the study of the nucleus. The nucleus or kernel of an atom is in ultimate control of all its properties and features, for such of these as do not depend directly on it depend upon the number and arrangement of the orbital electrons, both of which are decided by the nuclear charge; further, the atomic weight is decided almost exclusively by the nuclear mass. Though in dealing with most of these properties it is usual to imagine the nucleus as a geometrical point endowed with mass and charge, the truth is far less simple and more interesting. Nuclei are structures built of elementary particles—some and maybe all of which are independently known to us—bound tightly together. It is of great importance to ascertain these structures, not only for their own sake, but because through understanding them we may become able to control and extend the transformations of nuclei from one kind to another—the processes of transmutation, some of which are already feasible. Several fields of research are apt to contribute to such an understanding. Accurate measurement of the masses of atoms, and of the masses and charges and other properties of the elementary particles, are the first two of these, and form the subject of the present article.

SOME thirty years have now elapsed since the atom-nucleus was first imagined. Before it could be conceived men had to discover and measure negative electrons, and evolve the idea that these corpuscles normally reside in atoms, which in that case must comprise positive charges as well. Since an electron is less than one one-thousandth as massive as the lightest kind of atom, it is natural to suppose that the positive charges within an atom are linked with the main mass thereof. From this it is but a step to the notion of a heavy positive nucleus serving as central sun of the atom, with electrons revolving around it after the fashion of planets. This step was taken in 1904 (by Rutherford, and on the other side of the world by Nagaoka). A few years later, the picture was made more precise by assigning a definite number of circling electrons to every kind of atom—that is to say, to the atoms of all the elements; this at first was rather vaguely estimated at about half of the atomic weight of the element in question; then in 1915 it was chosen equal to the atomic number (customarily called Z) which marks the place of the element in the periodic table. Everything since discovered has justified this choice. It necessarily fixes the positive charge of the nucleus, which must exactly balance the total of the charges on the Z electrons, since the

atom as a whole is neutral; to the atom-nuclei of the Zth element of the periodic table it therefore assigns the positive charge Ze.

In so far as the circling or "orbital" electrons are concerned, the details of this atom-model have suffered change after change in the lapse of thirty years. Classical mechanics has given way to one form after another of "quantum" mechanics; the electron-orbits at times have been defined with the utmost exactitude, at other times they have been merged into wide and hazily-bounded zones; the electrons themselves have appeared sometimes as simple corpuscles, sometimes as corpuscles with a magnet superadded, sometimes as particles implicated with a wave-motion and sometimes as a continuous haze of fluid charge. All the while, however, some of the features of the model have remained undisturbed. Among these are the total number of the electrons chosen equal to Z, and the conception of the nucleus seated at the heart of the electronic system with the positive charge Ze and most of the mass of the atom concentrated upon itself. To the problems of this nucleus we now address ourselves.

First a few words about its size, which incidentally will recall the best of the evidence for its existence. The nuclear atom-model was transformed from a pretty speculation into almost a reality, when in 1913 Rutherford, Geiger and Marsden observed the deviations of a shower of alpha-particles projected against a sheet of gold foil.[1] Alpha-particles are atom-nuclei of the second element of the periodic table, helium ($Z = 2$); gold is the seventy-ninth element ($Z = 79$). The observed law of the deviations—that is to say, the distribution-in-angle of the deflected alpha-particles—is superbly well accounted for by assuming that within every atom of gold there is a center of force, the origin of just such an inverse-square central field as would surround a charge $+ 79e$; and that the alpha-particles are themselves point-charges of amount $+ 2e$, which are deflected by the forces which they suffer in passing through these fields. The concordance between the observed distribution-in-angle, and that which was deduced from these assumptions, extends to angles of deflection as great as 150°. Now under these assumptions, a particle which has had its path bent by as much as 150° has passed within $3.1 \cdot 10^{-12}$ cm. of the center of the central field. Inward as far as this, then, comes the inverse-square field; and whatever meaning we may later attach to such a vague expression as "size of the nucleus"—for size is an indefinite concept, in regard to anything which is neither tangible nor visible—the radius of the nucleus of the gold atom must assuredly be put at a value

[1] See my "Introduction to Contemporary Physics," pp. 72–92; or the second article of this series (*Bell Sys. Tech. Jour.*, January, 1924).

smaller than this. I will later speak more fully of the corresponding data for the few other kinds of atoms for which such studies have been made. In the meantime the reader may think of 10^{-12} and 10^{-13} cm. as reasonable guesses for the radii of atom-nuclei. They agree in order-of-magnitude with the value usually assigned for the radius of the electron, and are ten or a hundred thousandfold smaller than the radii of the atoms; so that, as many a writer has remarked, the nucleus and electrons bulk about as large in the atom which they make up as flies in a very great cathedral.

Small as it is, an atom-nucleus cannot be regarded as an elementary and an ultimate particle. No sooner had the physicists of a generation ago divided the "indivisible atom" of the nineteenth century mentally into electrons and a nucleus, than they found themselves obliged to go on with the division. The electron so far has escaped this surgery, but the nucleus has been resolved—mentally, again—into as many parts as the rest of the atom itself. The arguments are two. In respect of their masses, the nuclei of the many kinds of atoms which are known are so related among one another as to suggest that all of them are aggregates of diverse numbers of particles of a very few fundamental kinds, all those of a kind having quite the same charge and almost the same mass wherever they appear. Moreover, particles sometimes spring out of atoms—from certain elements spontaneously, from others only under the bombardment of such missiles as alpha-particles—which are of such a nature that their source must be sought in or about the nuclei of the atoms whence they come. The two arguments coalesce when it is noticed that the particles which must be postulated for the one are some of those which are observed in the phenomena on which the other is based. The masses of atom-nuclei imply that they are built out of certain kinds of bricks, and bricks of these very kinds are indeed observed at times, falling or plunging or being violently hurled out of disintegrating atoms.

The study of the nucleus therefore involves, to begin with, the measurement of its mass—the measurement of the masses of all the known kinds of nuclei, amounting by now to several hundreds. This seems to be the same as the basic task of chemistry, the task of measuring atomic weights. Yet in spite of the indescribable labor which numberless chemists have lavished upon atomic weights, their data are seldom of value in modern nuclear physics. This is because the atoms of most elements are of two or more different kinds (isotopes) with different masses. Chemical methods yield an average of their weights, but the student of the nucleus wants the mass of each kind separately; and this nearly always requires a physical method of

measurement, which only of late years has been brought to the requisite grade of accuracy. Even by this method the datum is not the mass of a nucleus, but of an atom; from it one must subtract the masses of the orbital electrons.

Next comes the measurement of the masses and charges of the fragments of nuclei which have fallen apart of themselves or been broken apart by missiles; these being, as I said, the bricks out of which it is tentatively assumed that nuclei are built up. Three of them have been identified as the electron, the proton, and the alpha-particle. The two last-named are the nuclei of the two lightest elements, hydrogen and helium respectively; their masses have been determined as accurately as that of the electron itself, while their (positive) charges have been found equal to $+e$ and to $+2e$ respectively. Further, there is the strange new uncharged particle called "neutron," discovered less than a year and a half ago among the rays proceeding from atoms of beryllium exposed to alpha-particle bombardment; and there is the yet newer "positive electron," springing out from what seem to be explosions provoked in nuclei by cosmic rays. Such a variety of bricks is not entirely welcome; it would be more elegant to design nucleus-models out of two fundamental particles only, say the proton and the negative electron, as once seemed possible; but we must take our building-materials as we find them. Perhaps, though, it will prove permissible to argue that some of these particles are not pre-existent in the nucleus, but are created when something crashes into it.

When fragments of charge and mass come out of a disintegrating nucleus, energy comes along with them; their kinetic energy in the first place, and in addition (in many cases) parcels of energy in the form of photons or corpuscles of light. A typical instance is that of the element radium C, of which a nucleus may disintegrate of its own volition, ejecting an alpha-particle and one or more corpuscles of light, and becoming—that is to say, the residue *is*—a nucleus of another element, radium D. The latter of these nuclei differs from the former in respect of the lost charge ($+2e$), the lost mass, and the lost energy. The third of these differences must be measured, along with the other two; to do this one must measure the velocity and mass of the emitted particle (or particles) of electricity and matter, and the wave-lengths of the emitted light.

It is not the custom to assume that when corpuscles of light are emitted from an atom, they must previously have existed as such within the atom. Protons and electrons are supposed to be durable, whether or not they are bound with one another into a nucleus; alpha-

particles are supposed either to endure, or else to be resolved into durable protons and electrons; but photons are regarded as mere transitory vehicles of energy, which gathers itself up into them when they are emitted, and disperses itself into other forms when they are absorbed. The energy, however, is supposed to share in the mass of whatever atom or nucleus it inhabits. In relativistic mechanics, energy E is always endowed with mass E/c^2, and mass m with energy mc^2; so that when a quantity of energy ΔE departs from a nucleus in the form of a photon (or, for that matter, in any other form) the mass of what is left behind is automatically reduced by the amount $\Delta E/c^2$. Thus to compute the mass of a RaC nucleus from that of a RaD nucleus, we should have to subtract from the latter not only the mass of the alpha-particle, but also that which departed with the emitted light.

Of course these statements about energy and mass are not to be taken as *necessarily* true, albeit they are based directly on the restricted theory of relativity, for the validity of which there is excellent evidence. On the contrary, one of the most alluring promises of the study of nuclei—for the speculative physicist—is that of testing the interconnection of energy and mass which relativity suggests. In the meantime, it is quite generally taken for granted. Notice an interesting corollary: the mass of an aggregation of electrified particles (such as a nucleus is) will not in general be the sum of the masses which its individuals have when far away from one another, for as these particles come together they may radiate energy, whereof the mass must be deducted from the sum of their masses. We shall see that this is commonly accepted to explain the fact that the mass of a nucleus is not quite equal to the sum of the masses of the protons, electrons, and other "bricks" out of which there is reason for assuming it to be built.

Thus from stable nuclei, we may learn their masses; from unstable or self-disintegrating nuclei, something about their constituents, and the energy-difference and mass-difference between the nucleus before and its fragments after its collapse; from nuclei disrupted by impact of projectiles, something about their constituents and something about their energy-content. There is much more to be measured. Some kinds of nuclei endure for æons, others break up in a time measured in millionths of a second; some have alternative ways of breaking up, a certain fraction following one and the remainder the other; some may be disrupted by impact of alpha-particles, some by protons, some by both and some apparently by neither. It is certain that all of these things are indications of the structure of the nucleus, but most are still too difficult to read.

A great part of contemporary physics consists of the analysis and interpretation of spectra; one wonders whether in this vast and tangled array of data there is information about nuclei? The answer must be phrased with care. The spectrum of an atom is due to its orbital electrons, and of these the number and the arrangement are controlled by the nuclear charge, which therefore dominates the spectrum; spectroscopy is full of evidence for the theorem which I set down at the start, that $+Ze$ is the nuclear charge of the element of atomic number Z. The mass of the nucleus is much less influential, owing to the enormous disparity between it and the masses of the electrons. Were it and they of the same order of magnitude, the nucleus would move like the electrons, revolving around the center of mass of the atom with a kinetic energy comparable with theirs. The emission of light would then entail a contribution from the kinetic energy of the nucleus as well as from those of the electrons, and the frequencies of the spectrum-lines would be affected by the nuclear mass. But the nucleus is so massive, its motion so slight and its kinetic energy so insignificant, that in nearly all atoms that contribution is too small to be appreciable, and the spectrum-lines are sensibly the same as if the electrons revolved around a perfectly motionless centre. The only exceptions are the three lightest kinds of atoms; I will later explain how the discovery of one of these was brought about, two years ago, by the influence of the mass of its nucleus upon the frequencies of its spectrum-lines.

The spectra of molecules are more dependent on nuclear masses than are those of atoms; for, when two (or more) nuclei and their attendant orbital electrons are combined into a single system, the balance of forces is such as to provide for each nucleus a position of equilibrium, from which it may be displaced and about which it will oscillate more or less like a pendulum. There are (for instance) two kinds of chlorine atoms, of nuclear masses standing to one another approximately as 35 to 37; consequently there are three kinds of diatomic molecules in ordinary chlorine gas, built as indicated by the symbols $Cl^{35}Cl^{35}$, $Cl^{35}Cl^{37}$, $Cl^{37}Cl^{37}$. In all of these three kinds of molecules the internal forces are very nearly the same, being determined by the charges of the nuclei and electrons which are identical for all three, and by their arrangement which is nearly identical; but the masses of the nuclei are different, and therefore so are their frequencies of oscillation, which appear in the spectra. The differences of nuclear masses also entail differences in the moments of inertia of these three kinds of molecules, which likewise are reflected in their spectra. The lines of molecular spectra are often doubled or

tripled by virtue of the presence of two or three kinds of molecules differing only in nuclear masses.

More recondite is another influence of nuclei on spectra, which is due neither to their charge nor to their mass. It often happens that what appears with an ordinary spectroscope to be a single line is resolved by an excellent instrument into several, although the earlier theory affirmed quite decisively that it should be single and simple. By "the earlier theory" I mean one which was substantially like the atomic theory of today, except that it involved the assumption that the field whereby the nucleus acts upon its attendant electrons is purely an inverse-square electrostatic field. If we suppose that in addition to this there is a magnetic field—that the nucleus is not only a charged body, but also a minute magnet acting upon or (to use a commoner term) "coupled with" the orbital electrons by the magnetic as well as by the electric field—then the subdivision of these apparently simple lines into clusters begins to become intelligible. It is well known that spectrum lines are split into clusters by the action of an external magnetic field—the Zeeman effect; it is natural to expect a magnetic field applied to the orbital electrons from the center of the atom to have somewhat the same effect as one applied from without, and to produce these permanent splittings, which are known as "hyperfine structure." Magnetic moment is attended with angular momentum, inasmuch as magnetism is due to whirling of electric charge; and some physicists prefer to regard the latter as primary, and to say that the subdivision of the lines is due to some unspecified kind of an interaction between the angular momenta or the "spins" of the nucleus and the orbital electrons. To the ones, the hyperfine structure yields the spin of the nucleus; to the others, its magnetic moment. These are intricate questions, to which it will be necessary to devote much space.

The nucleus is a magnet; the incessant circlings of each electron in its orbit constitute another magnet, a charge revolving in a closed path being equivalent to a current flowing in a closed circuit; and finally, it has proved essential for spectrum analysis to assume that each electron is in itself, quite apart from its motion, a magnet. The magnetic moment of the atom as a whole is the resultant of these three component moments, or rather groups of moments, since there may be many electrons and many orbits to a single atom. Now, this resultant may be measured, for instance by the method of Gerlach and Stern, in which a stream of atoms is deflected by a non-uniform magnetic field; and if there is ground for believing that one knows what part of the resultant is due to the electronic moments, then one

can deduce the magnetic moment of the nucleus itself. This has already been done in several cases. Perhaps it will be possible in time to attribute the magnetic properties of solid bodies, even of ferromagnetics, in part to their nuclei; but probably that is looking a long way ahead.

One more participation of the nucleus in phenomena remains to be recorded. The passage of X-rays and gamma-rays—that is to say, high-frequency light—through strata of matter has been abundantly studied. For the most part it is admirably well accounted for by supposing that the corpuscles of these rays possess the power, and only the power, of expelling orbital electrons from atoms through which they pass; any particular corpuscle either makes such an expulsion and vanishes or loses energy in doing so, or else it goes through the substance unaffected. There are two alternative modes of expulsion, but that is a detail into which we need not enter now. The relevant point now is, that with certain kinds of atoms and with particularly high frequencies of light it appears that these processes are not the whole of what is happening. The absorption and the scattering of X-rays are greater than they should be, if the photons interacted only with orbital electrons; and it is supposed that the excess is due to interactions with nuclei. Presumably it would be greater with the rays of immeasurably high frequency which probably form a part of the cosmic radiation.

Nuclei, then, contain almost the whole of the mass of ponderable matter. They are the seat of radioactivity. They may be disrupted by impacts of other and lighter nuclei, possibly by electrons and photons. They influence spectra through their charges and their masses, and through the closely-connected qualities of magnetic moment and angular momentum. Through their magnetic moments they are responsible in part for the magnetic properties of atoms and of larger pieces of matter. They interact with high-frequency X-rays. Such is the range of phenomena in which the nucleus takes a significant part, and out of which, therefore, the properties of the nucleus are to be derived.

In the present article I will describe and discuss these phenomena in succession. Some have been treated already in earlier articles in this journal, a fact of which I will avail myself to shorten this one, which nevertheless must extend into following issues.

The Elementary Particles

There are now six different kinds of material corpuscles known by direct experiment, of which there is more or less reason to believe that

they enter into the structure of some at least among the nuclei. These are:

The *proton*, or nucleus of the most usual kind of hydrogen atom;

The *alpha-particle*, or nucleus of the helium atom;

The *electron* (that is to say, the negatively-charged corpuscle customarily known by that name);

The *neutron*;

The *positive electron*;

The H^2 *nucleus* or *deuton*, the nucleus of an unusual kind of hydrogen atom of double the mass of the usual kind.

Of these six the first three have been known for years. They have actually been observed to spring out of nuclei, spontaneously in some cases, in others elicited by bombardment; and this is one of the two major reasons for imagining them as parts of nuclear structures. It is true that this reason does not apply directly to all kernels. Those which are known to emit alpha-particles spontaneously are a small fraction, a tenth or thereabouts, of the total number; and all but possibly two belong to the uppermost end of the periodic table, to massive atoms of atomic weight superior to 200. Those which are known to emit electrons are yet fewer, and again all but two belong to the most massive group. (The two exceptions are potassium and rubidium.) No kernel is known to emit protons spontaneously; but a great many elements both light and heavy will yield charged particles out of their nuclei, when suitably bombarded; and these have been proved in some cases to be alpha-particles, in others to be protons. Moreover the bombarding particles which achieve these results are themselves alpha-particles and protons, and there is reason to believe that sometimes these are actually absorbed into nuclei which they strike.

The other major reason for inserting protons, alpha-particles and electrons into our tentative models of nuclei is deduced from the masses and the charges of these bodies. There is a certain well-known standard of mass, one sixteenth of the mass of an oxygen atom; and the masses of all nuclei come fairly close to being integer multiples of this standard. Of course this can also be said about any other mass lying within a certain (narrow) range of the standard just defined, and perhaps it would seem better to say that the nuclear masses come fairly close to having a greatest common divisor of that order of magnitude, and then to determine by the method of least squares what number had best be chosen for this greatest common divisor. This procedure, however, would not be wise, unless the departures of the various masses from the integer-multiple rule were casual, whereas

it is extremely probable (to say the least) that they are systematic, and are indices of the structures of the nuclei. The choice of a definite standard must therefore be based on expediency or on theory, and none better than the present one has been proposed.

It would be pleasant to say that this standard is exactly the same as the mass of the proton, and thence to deduce that every nucleus consists of protons entirely. As a matter of fact, there is a difference of about three quarters of one per cent, the standard being lighter than the free proton; but this by itself is no bar to the hypothesis that all nuclei are made up of protons, since it is compatible with the general theory of electricity that charged particles when crowded close together should individually have smaller masses than when they are far apart. It is not, however, admissible to assume that these protons of reduced mass are all that the nucleus comprises. Were this so, the positive charge of a kernel of mass NM_s (M_s standing for the standard mass, N for any integer) would be $+ Ne$; but it is always (except in the case of hydrogen) observed to be less than this amount—it is equal to Ze, where Z stands for some integer less than N; and one must assume that there are $(N - Z)$ electrons present to cancel the difference between Ne and the actual charge. As for the alpha-particle, its mass and charge suggest that it consists of four protons and two electrons, and the masses and charges of certain heavier nuclei—carbon and oxygen supply the most vivid examples—suggest that within them the protons and electrons are united in groups of four and two to constitute alpha-particles, a substructure within the main structure.

Until a year or two ago, models of nuclei were constructed exclusively out of protons and electrons, sometimes grouped into alpha-particles and sometimes not. The discovery of the three new particles put an end to this era. The interlopers were not entirely welcome; deficient as the prevailing models had proved to be in many ways, people had become accustomed to them, and various eminent physicists were quoted as deploring—in informal and jocular words—the necessity of tearing them down and rebuilding with the new bricks among the old. Nevertheless, neutrons have been observed to spring out of nuclei, and positive electrons have been observed wandering about in space, sometimes among what seem to be the fragments of a kernel ruined by an impact so violent as to provoke an internal explosion. The new kind of hydrogen nucleus is sufficiently low in mass to suggest that it may be a building-stone in the construction of kernels heavier than itself.

The histories of the discoveries of these three particles have not

yet been related in the pages of this journal, and as they are extremely interesting portions of the most strictly contemporary physics, they well deserve some pages of description.

The Neutron [2]

It had been known since 1919 that certain light elements emit protons when they are bombarded by alpha-particles; these, however, are not "penetrating" rays, in the sense in which that term is commonly used, inasmuch as they are completely stopped by a layer of metal a fraction of a millimetre thick. The discovery of the neutron was the outcome of an attempt to detect penetrating rays emitted by the bombarded atoms. Bothe and H. Becker made this attempt, surrounding the source of alpha-particles and the substance on which they impinged by two millimetres of zinc and brass, and detecting what got through this barrier by means of a Geiger point-counter. Four elements—lithium, boron, fluorine and especially beryllium—produced an unmistakable effect. Bothe and Becker ascribed this to high-frequency gamma-rays or photons. It was indeed largely due to such photons; but mingled with these there were particles of another nature, as the further experiments of Irène Curie, Joliot and Chadwick were to prove.

To appreciate the proof it is necessary to realize that what is observed is an indirect rather than the direct effect of the corpuscles coming from the atoms bombarded by the alpha-rays. It is ionization of gas which is observed—ionization coming in spurts, which may be separately observed and counted by use of a Geiger counter or a quick-acting electroscope with proper amplifiers or an expansion-chamber, or may be summed up by the accumulation of charge in a slow-acting electrometer. The spurts of ionization are due to the transits of corpuscles across the gas, corpuscles which sometimes at least are recognizably electrons or atom-nuclei. But it is not to be taken for granted that these directly-ionizing corpuscles spring from the source of the phenomena, the element bombarded by the alpha-particles. They start their flights in the matter environing the source, being launched on their courses by invisible agents which are presumably the true primary rays coming from the source. What is observed, therefore, depends on the matter surrounding the source; and the last step leading up to the identification of the neutron was taken when Curie and Joliot interposed thin screens of various substances in the path of the primary rays from the source to the ionization-chamber.

[2] For a fuller account cf. an article of mine in *Review of Scientific Instruments*, 4, 58–63 (February, 1933).

When the screens were of metal, nothing sensational happened; but *if they were of paraffin, water or cellophane*—materials containing *hydrogen—the ionization-current went up instead of down.* This was not the first time that a screen had been observed to enhance the effect of what supposedly were gamma-rays, but in the previous cases it was permissible to infer that the rays were expelling electrons from the substance of the screen. Here the substances were distinguished not by abundance of electrons, but by abundance of hydrogen atoms in their structure; and Curie and Joliot conceived the idea that the primary rays were ejecting protons from the screen, which entered the chamber and in it ionized abundantly. This theory they fortified at once by applying magnetic fields, and finding that the ionization persisted (electrons issuing from the paraffin would have been twisted back, unless extremely fast); by interposing 0.2 mm. of aluminium, and finding that the extra ionization ceased (electrons, if extremely fast, might have got through); and by taking cloud-chamber photographs, and observing tracks of the aspect of proton-tracks springing out of the paraffin and traversing the ionization-chamber partly or altogether.

At once it was guessed by Curie and Joliot that these protons were recoiling from elastic impacts of the high-energy photons which the primary rays were still supposed to be—that they had suffered, in fact, the very same sort of blow as electrons suffer in the well-known "Compton effect." So great, however, was the energy of the protons (as evinced by their range) that photons of energy almost incredibly great had to be postulated; such would probably have an even greater penetrating power than that of the primary rays, and there were other objections more or less solidly founded on theory, which now it would be scarcely worth while to discuss. The French physicists were aware of these difficulties, and published them; but it was reserved for one of the Cavendish group to reject the idea altogether, and supplant it with the one which at present is accepted. Chadwick seized upon the revelations from the Institut du Radium with such alacrity that within six weeks he was reporting data obtained by counters and by cloud-chambers—data which confirmed that the rays emitted from beryllium when bombarded by alpha-particles are able to confer great speeds not only upon protons, but on nuclei of other elements of low mass (a later list comprises Li, He, Be, B, C, N, O, A; and Kirsch has very recently detected emission of neutrons from many more). Out of these data emerges the fact which speaks most clearly for his theory that the corpuscles which impel the protons and other nuclei are material particles of nearly the mass of a proton, instead of being corpuscles of light.

The argument is as follows: For simplicity let us consider solely the nuclei which are projected in directions pointing straight away from the source of the primary rays, and therefore must have suffered central impacts. Specially, let us take the cases of hydrogen and nitrogen nuclei thus projected. The ranges of these have been measured (of N by Feather, of H by various physicists) and their maximum speeds deduced by means of knowledge earlier acquired of the range-vs.-speed relations of charged particles. The values of speed accepted by Chadwick are $3.3 \cdot 10^9$ and $4.72 \cdot 10^8$, respectively. Now if the corpuscles which in central impacts gave to these nuclei these speeds were photons, it is easy to compute by the Compton-effect equations the energy U of the photons; if the impinging corpuscles were material particles of mass M and speed v, it is easy to compute both v and M. It turns out that by the first procedure, one gets different values of U from the two cases (55 and 90 million electron-volts, respectively); by the second, one gets compatible values of M and v. With the first theory, then, one would have to say that nuclei of different kinds were struck by different photons. This is not quite inconceivable, as there *might* be a mixture of gamma-rays of different energies, and a greater likelihood of the higher-energy photons interacting with the more massive nuclei. But it seems less acceptable than the other theory, which permits one to postulate a single kind of corpuscle to explain the impacts against both kinds of nucleus. This corpuscle must be neutral, as a particle of charge e and the computed mass and speed could never penetrate nearly as thick a layer of matter as it can traverse; it is therefore called the "neutron."

The value of M deduced from the foregoing data is given as 1.15 times that of the hydrogen nucleus; the possible error in the estimate of the speed of the recoiling nitrogen nuclei is such that Chadwick says "it is legitimate to conclude that the mass of the neutron is very nearly the same as the mass of the proton." An estimate ostensibly much closer ($1.007 \pm .005$) has been made by a train of reasoning which I will later quote.

The Positive Electron

Whereas the discovery of the neutron came about through the study of transmutation, the positive electron came to light in the course of cosmic-ray research. The ionization of the atmosphere, whereby the cosmic rays are manifested, is due directly to fast-flying corpuscles which leave behind them trails of ionized molecules fairly close together (on the average, about a hundred ion-pairs per cm. in air at sea-level atmospheric pressure). The trails may be made visible by

the classical method of the expansion-chamber (Figs. 1 and 2). The particles may be tested for their charge by having a magnetic field pervading the chamber. Some of the paths are then found to be smoothly curved, proving beyond a doubt that the corpuscles are charged.[3]

The sign of the curvature of a path in a magnetic field should disclose the sign of the charge of the responsible corpuscle; but here

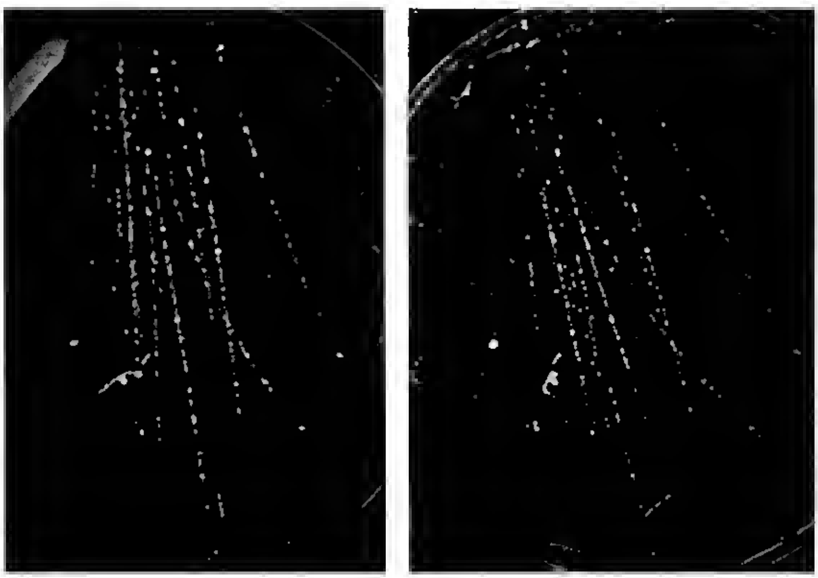

Fig. 1—Two photographs (taken from different viewpoints) of a nuclear explosion, probably that of a copper nucleus struck by a cosmic ray. The tracks on the right, and concave to the right, are those of positive electrons; others are due to negative electrons. (P. M. S. Blackett; *Proceedings of the Royal Society.*)

appears a difficulty: the sign cannot be inferred unless the sense in which the corpuscle described the path be known, and there is nothing whatever about the aspect of an ordinary trail to indicate that sense. It might be guessed that the particle is necessarily moving downward rather than upward, since the cosmic rays come from above. This, however, would be a bad guess, for some at least among the trail-making corpuscles are secondaries set into motion by the primary rays, as protons are known to be impelled by neutrons, and electrons by photons; and some of these secondaries may be, and indeed certainly

[3] Other paths seem quite straight, but there is strong reason to believe that a neutral particle would not produce anywhere nearly so great a density of ion-pairs as is observed along them, and it is inferred that they are due to charged particles which are moving with too much momentum to be sensibly deflected.

are, moving upward. One therefore has to await, or to produce, some unusual event to reveal the sense of the traversal of a path.

One such event is portrayed in Fig. 1. It is certainly one of the most deep-seated of human convictions that when tracks are seen to radiate from a common point, the objects which made them must have

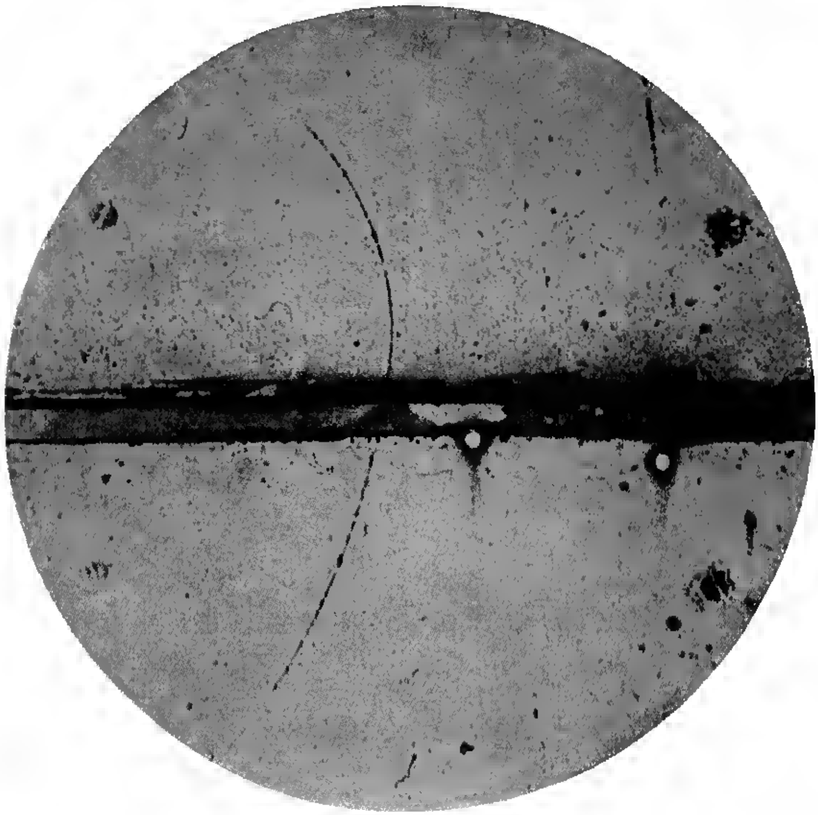

Fig. 2—Track of a positive electron which traverses a lead plate 6 mm thick, and has energy amounting to 63 million electron-volts before it enters the lead. (C. D. Anderson; *Physical Review.*)

travelled outward and not inward, except possibly for one which may have provoked the flying-asunder of the rest. Here is such a situation. The radiant point was in the midst of a mass of copper wire surrounding the expansion-chamber, and it is probable though not certain that the event was the explosion of a copper nucleus provoked by a cosmic ray. Among the radiating paths, curvatures of opposite senses occur; and this practically proves that charged particles of both signs are present.

Several other such photographs were taken by Blackett and Occhialini in Cambridge (England) and by Anderson in Pasadena.

Events of another type are observed, when the mixture of neutrons and photons emitted from beryllium bombarded by alpha-particles is allowed to fall upon a metal plate: the tracks of many ionizing corpuscles are noticed springing from the plate, and when there is a magnetic field applied, some are seen to be curved one way and some the other. Yet another is exemplified in Fig. 2. This is a historic photograph, the one from which the positive electron was first inferred (by C. D. Anderson); it is rarely that one can fix with such precision the moment of a major discovery, and perpetuate the very observation out of which it was made. Here obviously is the path of a single particle coming from below, which has cloven entirely through the lead plate of 6 mm. thickness, and has emerged from the upper side with diminished speed revealed by the augmented curvature of the trail. It is this change of curvature which fixes the sense of the traversal of the path, and the sign of the curvature thereupon fixes the sign of the particle's charge as positive.

But granted that many of the ionizing corpuscles which interlace the air are positively charged: are they not simply alpha-particles or protons, or of some other well-known type of positive ion? Here enters the second item of the evidence. Assuming (e.g.) the agent of the trail of Fig. 2 to be a proton, one may calculate the speed which it would necessarily have, in order to suffer a curvature-of-path equal in magnitude to that which is observed. One may then evaluate, from prior knowledge, the number of ion-pairs per unit length of trail which it would produce; and this turns out to be many times as great as that which is observed. A proton would produce a trail much denser, and also much shorter, than the actual one; its energy would be used up in a progress of 5 mm. away from the plate, whereas the visible course of this corpuscle extends for more than 5 cm. and shows no sign (in thickening or in increase of curvature) of being near its end.

The particle of Fig. 2 was therefore not a proton, nor, *a fortiori*, an alpha-particle or more massive ion; and the only way to reconcile the observed curvature with the observed density of path seems to be, to assume a particle about the same as the electron both in mass and in magnitude of charge, though not in sign of charge. This is not the same as saying that either the charge or the mass is accurately determined. Apparently it is certain that the charge must be less than $+ 2e$, which makes it equal either to $1e$ or to some non-integer multiple of e, and the latter alternative is too painful to be borne. As for the mass, it must be many times smaller than that of the proton (if the

charge is e), but to say more would be premature. The basis for supposing it equal to the mass of the electron is the feeling that there ought not to be any other fundamental masses in Nature than we knew already, together with certain suggestions from the quantum-mechanical theories of Dirac. The estimation of the mass may be bettered, if it is possible to observe collisions between positive and negative electrons with the expansion-chamber and to trace the paths of the colliding particles; there are reports that this has already been done with some success.

The action of cosmic rays being something which we cannot intensify nor control, it is doubly fortunate that another agent has already been discovered which is capable of generating positive electrons; for these particles have been observed, by several people in several different schools, leaping out of sheets of metal bombarded by "hard" or high-frequency gamma-rays. At the first observations, the bombarding radiation was a mixture of gamma-rays with neutrons, and it was not unnatural to suppose that so novel a result must be due to the action of the novel kind of corpuscle. Perhaps in those experiments the neutron did participate in the effect; but it has now been found—by Anderson and Neddermeyer in Pasadena, by Meitner and Philipp in Berlin—that gamma-rays suffice. Those employed so far are chiefly, if not altogether, the radiation from thorium C″ consisting of photons of energy 2.6 millions of electron-volts.

A theory quite extraordinary, indeed by all prior concepts revolutionary, has been propounded by Blackett and Occhialini: it is the idea that the photon converts itself into a pair of electrons, positive and negative respectively. The net charge of the universe is not altered by such a process, since the two created charges balance one another; neither is the total mass of the universe, for the masses of the two electrons (including the kinetic energy wherewith they are endowed) are equal altogether to that of the vanished photon. For this theory it may be said, in the first place, that positive electrons frequently appear jointly with negatives, one particle of each kind springing forth from a single point: Anderson and Neddermeyer have observed no fewer than 22 of such cases. Moreover if the theory is true, the total kinetic energy of the two particles of such a pair—and *a fortiori* the kinetic energy of the positive electron by itself—must lie below a certain upper limit, which is computed by deducting a million electron-volts from the energy of the responsible photon; for this is the amount of energy which by Einstein's relation (which will figure prominently in the latter part of this article) must be used in building the electrons by themselves. Thus if in these experiments with

gamma-rays, either positive electrons or electron-pairs were to be observed with energy greater than 1.6 million electron-volts, the theory would be contradicted; but it turns out that the energies seem to lie just below this figure, never certainly above it. Positive electrons should not be produced at all by gamma-rays of which the photons have less than a million electron-volts of energy; and in fact none was found when Meitner and Philipp applied such rays to a metal. A much greater number of cases should be observed before the idea is affirmed; but if it should be confirmed the consequences would be highly important, not only for its own sake but because it is an offshoot of basic quantum-mechanical theory, which would thus be greatly strengthened. Incidentally it would then not be necessary to provide for positive electrons in our models of nuclei.

The H^2 Nucleus

This particle, for which physicists are having difficulty in finding the perfect name (*deuton*, *diproton*, *hemialpha particle*, and *demihelion* are among those which have been suggested), is the nucleus of the newly-discovered isotope of hydrogen, "deuterium." I will defer the history of the discovery of this isotope to the end of the article, as there are several things which should be told before it. There is no definite reason as yet for assuming that the deuton enters as such into the composition of yet more massive nuclei, but it may well prove a convenient stone for the building of nuclear models.

The Masses of the Elementary Particles

The remaining "elementary" particles—proton, alpha-particle, negative electron—have been known too long to require a special description. I will therefore give only a table of their masses and their charges, along with those of the other three; prefacing it with the statement that I have not been using "elementary" in the sense

Corpuscle	Mass in Terms of Grammes [4]	Mass in Terms of One Sixteenth the Mass of the Oxygen Atom [5]	Charge
Proton	$1.66 \cdot 10^{-24}$	1.0078	$+e$
Alpha-particle	$6.60 \cdot 10^{-24}$	4.002	$+2e$
Electron	$9.03 \cdot 10^{-28}$	.00054	$-e$
Neutron	$1.66 \cdot 10^{-24}$ ca.	1.007 ca.	0
Positive electron		(see page 341)	
H^2 nucleus	$3.31 \cdot 10^{-24}$	2.0129	$+e$

[4] From Birge's critical tabulation; the probable errors amount mostly to less than one digit in the last place quoted.

[5] See the following pages for probable errors.

of "ultimate"! It is possible, nay probable, that some of these corpuscles are built up from others. Neutron may be proton plus electron; proton may be neutron plus positive electron; alpha-particle may be two protons plus two neutrons, or four protons plus two electrons.

Masses of Atoms and Their Nuclei

If all the atoms of an element were perfectly alike, we could take the relative values of their masses—relative to those of other elements, and in particular to that old familiar standard, one sixteenth the mass of an oxygen atom—straight from the chemists' tables of atomic weights. It happens, however, that there are two, three, or several different kinds of atom to almost every element, and they are nearly always so thoroughly intermingled in even the smallest analyzable samples as to suggest that the mixing was done while the earth was still a gas. Whatever chemical method of measuring "atomic weight" be applied to an element (and this includes the strictly physical scheme of measuring its density when it is gaseous) leads forthright and inevitably to a mean value of the masses of its "isotopes" or divers kinds of atoms. Not a simple average, of course! but rather a weighted mean, to which every isotope makes contribution in proportion to its relative abundance in the mixture.

The tables of the "chemical atomic weights" are just collections of these weighted means. They nearly all involve two or more varieties of atoms, and in most of the cases the weighted average is markedly different from the mass of any isotope. Sometimes one of the isotopes predominates so greatly that the others contribute very little to the mean, and the chemical atomic weight is not a bad approximation to the mass of this single kind of atom. This is not typical of the system of the elements as a whole, but it happens to be the case of no fewer than eight among the first eleven: a coincidence which has had some influence on the trend of scientific thought, for if it had not happened the chemical atomic weights of seven among these eight elements would not have been so nearly integer multiples of the standard as they actually are (*viz.* H 1.01, He 4.00, Be 9.02, C 12.00, N 14.01, F 19.00, Na 23.00) and then it would have been difficult to advance the idea that all atoms are built up from common particles. If oxygen itself were not of the group of these eight—if the rarer isotopes of oxygen were, say, a tenth or a third as abundant as the predominant one, instead of being less than 1/500 as abundant—we should either be suffering from a table of atomic weights in which there would be no integers unless by accident, or else we should be using some other

PERIODIC TABLE OF THE ELEMENTS

(Values of atomic weights taken from the Third Report of the Committee on Atomic Weights; G. P. Baxter, *J. Am. Chem. Soc.*, 55, p. 451)

I	II	III	IV	V	VI	VII	VIII			O
1 H 1.0078										2 He 4.002
3 Li 6.940	4 Be 9.02	5 B 10.82	6 C 12.00	7 N 14.008	8 O 16.000	9 F 19.00				10 Ne 20.183
11 Na 22.997	12 Mg 24.32	13 Al 26.97	14 Si 28.06	15 P 31.02	16 S 32.06	17 Cl 35.457				18 A 39.944
19 K 39.10 29 Cu 63.57	20 Ca 40.08 30 Zn 65.38	21 Sc 45.10 31 Ga 69.72	22 Ti 47.90 32 Ge 72.60	23 V 50.95 33 As 74.93	24 Cr 52.01 34 Se 79.2	25 Mn 54.93 35 Br 79.916	26 Fe 55.84	27 Co 58.94	28 Ni 58.69	36 Kr 83.7
37 Rb 85.44 47 Ag 107.880	38 Sr 87.63 48 Cd 112.41	39 Yt 88.92 49 In 114.8	40 Zr 91.22 50 Sn 118.70	41 Nb 93.3 51 Sb 121.76	42 Mo 96.0 52 Te 127.5	43 Ma 53 I 126.92	44 Ru 101.7	45 Rh 102.91	46 Pd 106.7	54 Xe 131.3
55 Cs 132.81 79 Au 197.2	56 Ba 137.36 80 Hg 200.61	RARE EARTHS 81 Tl 204.39	72 Hf 178.6 82 Pb 207.22	73 Ta 181.4 83 Bi 209.00	74 W 184.0 84 Po	75 Re 186.31 85—	76 Os 190.8	77 Ir 193.1	78 Pt 195.23	86 Rn 222
87—	88 Ra 225.97	89 Ac	90 Th 232.12	91 Pa	92 U 238.14					

RARE EARTHS

57 La 138.92	58 Ce 140.13	59 Pr 140.92	60 Nd 144.27	61 Il	62 Sm 150.43	63 Eu 152.0	64 Gd 157.3
65 Tb 159.2	66 Dy 162.46	67 Ho 163.5	68 Er 167.64	69 Tm 169.4	70 Yb 173.5	71 Lu 175.0	

standard; I must leave it to some chemist to say which is the likelier alternative.

Despite these particular cases, it is a general rule that the masses of the atoms of an element cannot be ascertained, unless its isotopes are separated from each other and separately measured. Indeed, the exceptions to the rule are more apparent than real. One cannot be quite sure that any element is an exception, without performing upon it such an experiment as would separate its isotopes if there were more than one existing in a sensible amount. It is true that there are different radioactive isotopes of one and the same element, which come into being from different sources and therefore are not mixed with one another; but these are generally so scanty in amount that their atomic weights have not been measured at all. Thus every valid measurement of what can properly be called the mass or the weight of an atom requires an "isotope analysis" of the element in question.

The way of separating isotopes and the way of measuring the masses of their atoms are happily the same, although of course the latter aim demands a great refinement of the method over what is needed for the former. One sends a stream of ions of the element through a sequence of electric and magnetic fields, the first of which accelerates them to a considerable speed, while in the remaining field or fields they are deflected. The deflection depends upon the mass, so that ions of equal charges and different masses—and thus, ionized atoms of the different isotopes of a single element—arrive at different points of the photographic plate which receives them and registers their presence. When the scheme was introduced by J. J. Thomson, he considered it a method of chemical analysis: it was applied to the ions found in electric discharges in ordinary gases and mixtures of gases, and he expected to observe—and did observe—ionized molecules of compounds too unstable to be durable. Unexpectedly it turned out to be a method of ultra-chemical analysis, for when applied to the ions of a discharge in neon, it disclosed two kinds instead of one. Efforts were made to identify one of the two as something else than neon, but when they all failed, neon was registered as the first of the elements to be separated into isotopes.

This discovery was made in 1912, and then occurred the great hiatus of the war. The later story will be an easy matter for historians to trace, at least as far as 1933; for despite its obvious importance, this subject of research invited incredibly few workers. I cannot guess why, in times when many physicists were looking for experimental problems, it was so seldom chosen. There are just three names to be

mentioned (omitting the work of a few students on a special question, the relative abundance of the isotopes of lithium, and that of Bleakney on the isotopes of hydrogen and neon). Outstanding, and for years unique, is that of Aston of the Cavendish Laboratory, who took over the problem from Thomson and has bound up his name with isotopes by fourteen undeviating years of concentration. There are two stages of the post-war history: the period when isotopes were merely counted and their masses roughly estimated, and the period (in the midst of which we now stand) when their masses are measured with precision rivalling the vaunted accuracy of the chemical atomic weights, and also their relative proportions or "abundances" in the mixtures which we usually call elements. Aston initiated both these periods. In the earlier of them Dempster, who also had been trained before the war in the analysis of ions, separated several of the elements into their isotopes. Costa made a couple of very accurate measurements of mass, but then abandoned the field. Bainbridge entered it after the second period commenced, and is now measuring atomic masses with an exactitude equalling Aston's.

In Aston's apparatus the deflecting fields are disposed in an intricate and ingenious way, so that ions of equal mass shall be brought to the same point on the photographic plate even though their speeds be far from equal. This is because he usually derives his ions from a self-sustaining glow-discharge, of which the electric field serves as his accelerating field and imprints different speeds upon different ions of equal mass because they start from different places in the discharge. Much simpler are the schemes of Dempster and of Bainbridge, in which the sole deflecting agency is a uniform magnetic field, which swings the ions around in semicircles from the slit where they enter the deflection-chamber to the plate on which they impinge (Fig. 3). This, however, does not work properly unless all the ions of a particular mass have very nearly the same velocity, so that either they must leave the source with very low speeds and be subjected to the same and relatively large accelerating voltage (such was the case in Dempster's work) or else there must be some device for preventing all ions but those of a very narrow velocity-range from reaching the deflection-chamber. Bainbridge's device for this latter purpose is shown in Fig. 3; between the plates of the "velocity-filter" a transverse electric field is superposed on the magnetic field which is at right angles to the plane of the paper, and no charged particle gets through to the slit unless its speed is very nearly equal to the ratio of the field-strengths.

If a beam of ions all of identical mass M and charge e and speed v

were to enter the chamber through the slit they all would follow the same semicircle and assemble on the very same spot on the plate, the distance of which spot from the slit would tell the observer their mass. But when a beam of ions of a single element is projected through the slit, it is not usually a single spot which appears upon the plate. All students of physics have seen reproductions of such plates, chiefly from Aston's magnificently ample store. I reproduce

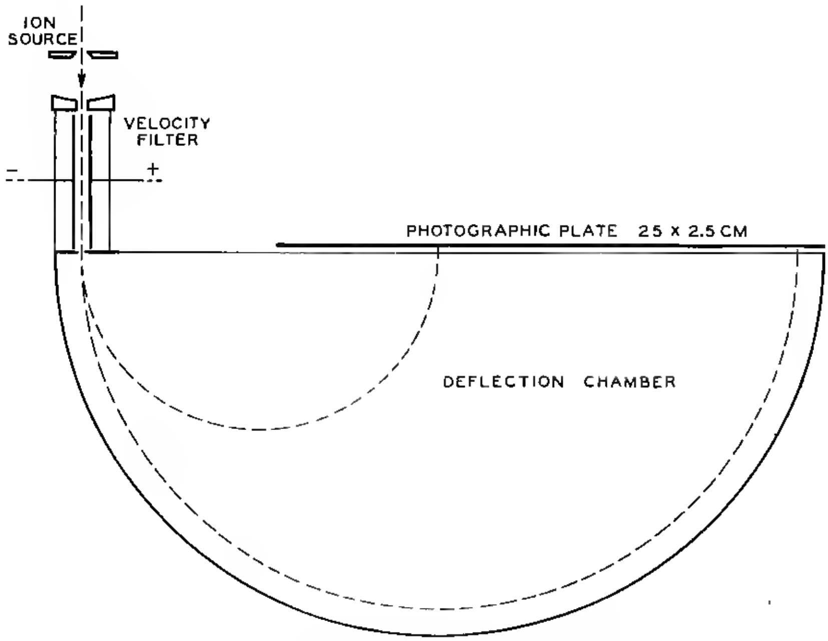

Fig. 3—Scheme of Bainbridge's apparatus for accurate measurement of the masses of isotopes.

here two from Bainbridge's, Fig. 4 for zinc and Fig. 5 for germanium. These are "mass-spectra" every spot or "line" of which is the evidence of a separate isotope of the element in question. Germanium and zinc are neither the least nor the most profuse in isotopes among the elements; there are still a few (fluorine and sodium, for instance) for which only one has been discovered, and at the other extreme there is tin with no fewer than eleven.

It is, of course, the charge-to-mass ratio of the ion rather than its mass which is deduced from the position of the spot and the strengths of the accelerating and deflecting fields. (There is no need of giving the formula here, as it is to be found in every textbook and is readily

derived.) The charge is usually $+ e$ (singly-ionized atom), sometimes $+ 2e$ (doubly-ionized atom), rarely $+ 3e$ or greater; there is no difficulty in telling which. No one goes to the trouble of determining mass or charge-to-mass ratio absolutely, with the full precision of which the method might be capable; what is actually evaluated is

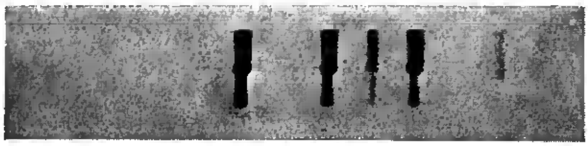

Fig. 4—Mass-spectrum of zinc (K. T. Bainbridge).

the ratio of the mass of each unknown to that of some familiar kind of atom, eventually always the atomic mass of the principal isotope of oxygen. There are various schemes and tricks for facilitating the comparisons, of interest chiefly to those who have some intention of imitating the experiments. Of more general interest is the problem of producing the ions.

The elements which are gaseous at ordinary temperatures, and those which have compounds that are gaseous at ordinary temperatures (such as carbon in CO and CO_2), and the metals which have high vapor-pressures such as mercury—these were analyzed early in the game.

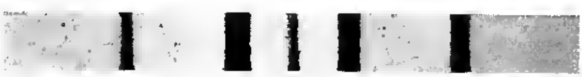

Fig. 5—Mass-spectrum of germanium (K. T. Bainbridge).

They are introduced into the discharge-tube, alone or mixed with other gases, and the processes of the discharge ionize their atoms (or the molecules of their compounds, which serve the purpose just as well). Certain others, the alkali metals and the alkaline earths in particular, were conquered through the fact that their ionized atoms stream out of their solid salts when these are heated or bombarded by electrons. The easier cases thus disposed of, it became necessary to lay siege by special artifice to most of those which remained. Constant readers of *Nature* are acquainted with the letters, generally two to four in a year, in which Aston announces the capture of one fortress after another. Sometimes it is the gift of a sample of some rare element which makes possible the new result, but oftener the contribution of some unusual compound of a common element which,

when introduced into the discharge-tube, vaporizes fast enough to supply the desired atoms to the discharge but not fast enough to inhibit the current or clog the tube. Curious observations have been made upon the behavior of some of these strange compounds in a current-carrying gas; of osmium tetroxide, for instance, Aston relates that it had upon the discharge an effect to be compared with the injection of a powerful drug into a living organism.

So much success has attended these efforts that the conquests yet remaining to be made are few, and it is a much quicker affair to list the as-yet-unanalyzed elements than the analyzed. In order of increasing atomic number (which I place in front of each symbol) they are: 43 Ma (a lately-discovered element); 45 Rh, 46 Pd (two members of the second of the "triads"); 61 to 71 inclusive, excepting 68 Er (ten rare-earth elements); 72 Hf (likewise lately discovered); 77 Ir, 78 Pt (two members of the third triad); 79 Au; and the elements beyond 84, of which all but three (88 Ra, 90 Th, 92 U), being unstable, are very scarce.[6] Some of these must owe their absence from the list of the conquered to their rarity, but many are common enough, and what is lacking is a way of driving their atoms into the open and ionizing them.

The other list, that of the analyzed elements, now comprises sixty-six. Among these are distributed nearly two hundred kinds of atoms of different masses. I count 198 in one of the tabulations, but of these some twelve or fifteen are marked as somewhat doubtful, because their ostensible lines on the plates are either very dim or else might be ascribed to some other kind of substance. (Thus if two kinds of ions are observed which differ in mass by one unit, it is often possible that the lighter may be an ionized atom and the heavier an ionized molecule of the hydride of that atom, instead of both of them being ionized atoms of unequal masses.) Among the 198 there are several of which the existence was first deduced from band-spectra; some of these have since been detected in mass-spectra, notably the minor isotopes of oxygen, O^{17} and O^{18} (I adopt the practice of writing atomic mass as a superscript to the chemical symbol); others, Be^8 and C^{13} for example, have not yet been confirmed in this manner, but the evidence from the bands is strong.

These nearly two hundred isotopes do not exhaust the list. There are in addition the radioactive atoms, of which there are known at present thirty-six varieties, distributed over the last twelve places of

[6] At the recent Chicago meeting of the A. A. A. S., Aston announced that he had analyzed uranium, finding a single isotope of mass about 238. This does not speak against the extra isotope of mass 234 appearing in Fig. 7, which is inferred from the study of radioactivity and is known to be too scanty to appear on Aston's plate.

the table of the elements (Z 81 to Z 92); and there are the seventeen elements of atomic number inferior to 81 which have not yet been analyzed, to each of which we must assign at least one isotope. This makes the round figure *two hundred and fifty* a suitable choice for the number of different masses of atoms, *the number of different kinds of nuclei, already known*. It may be a little excessive, but is not likely to remain so for long.[7]

A graphical presentation of these atomic masses is more effective by far than a table. One naturally thinks first of plotting A, the atomic mass, against Z, the atomic number; but then it turns out that the diagram is inconveniently high. The inconvenience is lessened in Figs. 6 and 7 by plotting $(A - Z)$ against Z, a scheme which has also some value for theory. All the isotopes of an element are marked by dots along its vertical line, and their mutual differences of mass are properly given; but in comparing the isotopes of any element with those of any other, one must think of their dots as vertically displaced by an amount equal to the difference between the abscissæ of the elements. The two figures refer, one to the elements below and the other to those in and above the great gap which in a single figure occurs at the as-yet-unanalyzed group of the rare earth elements. The slanting lines in Fig. 7 connect the consecutive members of radioactive families; they are too crowded to be clear, but I have shown a much clearer diagram in an earlier article of this series.[8]

Such a diagram implies that the masses of the isotopes are integer multiples of a common unit, that unit which is one sixteenth the mass of an oxygen atom; we must now examine into this question. Before mass-spectra were observed, the non-integer "atomic weights" of the chemical tables—such as the 24.32 of magnesium and the 35.46 of chlorine—were regarded as the masses of individual atoms. The discovery of isotope-analysis must have created, in some minds at any rate, the transitory hope that all true atomic masses would be proved to be exactly integers,—if not in terms of one sixteenth the oxygen mass, then in terms of some other. I do not know whether this hope was ever widely formed; in any case, it was doomed to be dashed. The ratios of the masses of the isotopes to one sixteenth the

[7] Absence of an isotope from the list of those discovered means, of course, not that it is absolutely non-existent, but that the ratio of its abundance to those of the major isotopes of the element in question must be below some critical least-observable amount. This critical amount varies so much with the element, the method, and the experimenter that no generally-valid figure can be given. In the very best cases (e.g. helium, with which a vigorous search for He^5 has been made) it is as low as one part in 40,000; in others, apparently as high as one in a few hundred.

[8] Number 12 ("Radioactivity"), this *Journal, 6*, 55–99, January, 1927.

mass of the O^{16} isotope are much more nearly integers than many of the chemical atomic weights, but they are not exactly integers. The most famous of all the chemical misfits—the ratio 1.008 to 16.000 of the combining weights of hydrogen and oxygen—is almost exactly

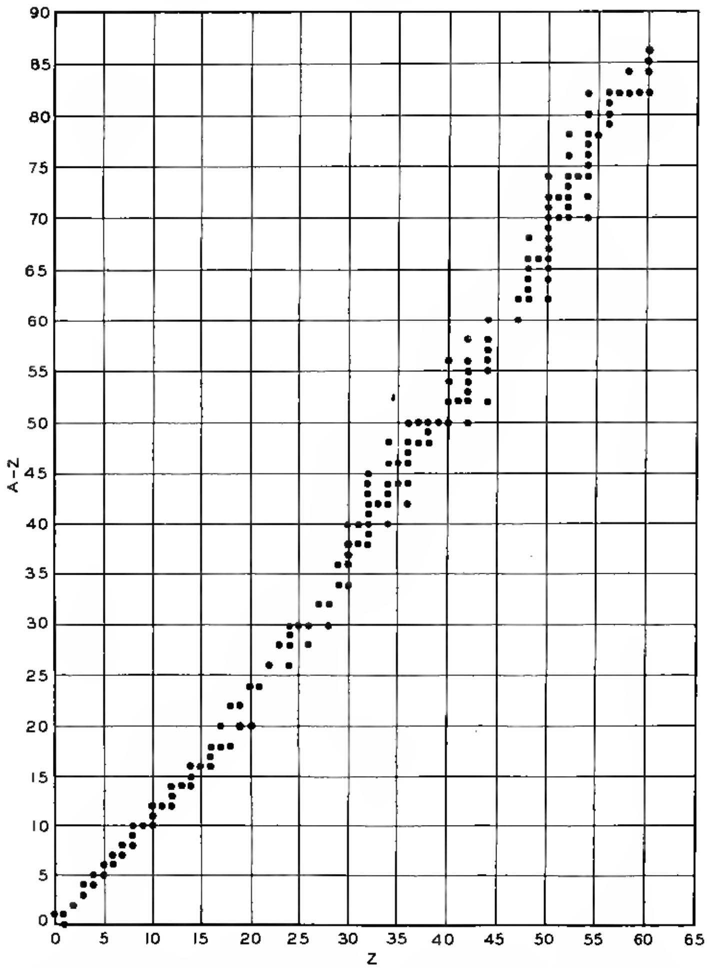

Fig. 6—Diagram of the isotopes of the elements of atomic numbers up to 60, the difference between mass-number A and atomic number Z being plotted against Z.

repeated between the isotopes; for both these elements are of the class in which one kind of atom predominates immensely over the rest. The ratio of the masses of the principal isotopes, H^1 and O^{16}, is one of those on which the highest resources of the technique of mass-

spectroscopy have been lavished; and it turns out (according to Bainbridge) to be 1.007775 ± .000035 to 16.00000. From another part of the table of the elements, take caesium. This is one of the few

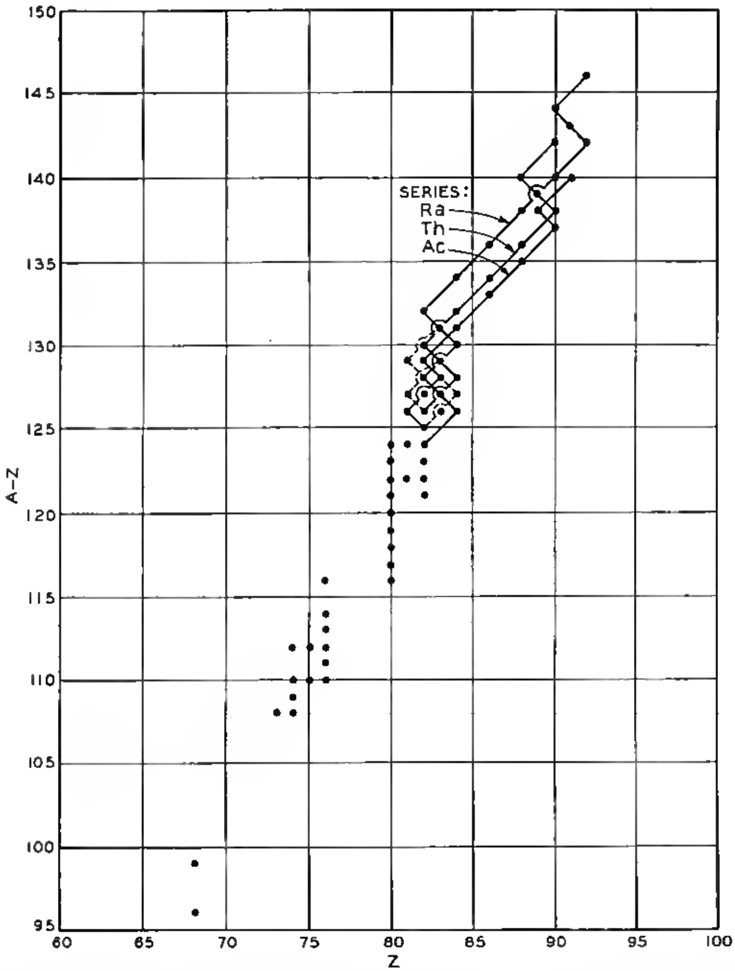

Fig. 7—Diagram of the isotopes of the elements of atomic numbers over 60. Lines connect isotopes belonging to one and the same radioactive series, most of which are known by their radioactivity alone. The mass of the end-product of the actinium series (AcD) is taken as 207 in accordance with Rutherford's opinion.

analyzed elements which as yet has disclosed no trace of more than one isotope, and the mass of this one amounts, in terms of "one sixteenth of O^{16}" to 132.93 ± 0.02.

Yet strange as it may seem, this failure of atomic masses to be integer multiples of either the mass of H^1 or one-sixteenth-the-mass-of-O^{16} is no detriment to theory, but rather the reverse. There is a very general hypothesis which may be phrased as follows: if a number of elementary particles cling together in a stable cluster, the mass of the cluster M is less than the sum Σm of the masses which the particles would have if they were free, and the difference $(\Sigma m - M)$ is the energy "of binding," the energy which would have to be given back to the particles of the cluster to disperse them again into freedom. I say "the difference of masses *is* energy," thus invoking Einstein's principle of the equivalence of energy and mass. By this principle a mass amounting to m grammes is an energy amounting to mc^2 ergs (c standing as usual for the speed of light in vacuo, $3 \cdot 10^{10}$) and an energy amounting to E ergs is a mass of E/c^2 grammes, whether it be kinetic energy or light or whatsoever other form.[9] If a nucleus be a cluster of, say, electrons and protons, then its mass must be less than the sum of their separated masses, for otherwise it would have no cohesion and would fall apart of itself; and its deficiency of mass is a measure of its stability.

At this point I ought to give some idea of the orders of magnitude involved. Nothing has been said thus far about the mass in grammes of any kind of atom, but we now require some such value in order to make the translations between energy expressed in ergs or in electron-volts, and mass expressed in terms of our standard one-sixteenth-of-O^{16}. The masses of atoms in grammes are not known nearly so well as their ratios to each other, but the three significant figures assured for oxygen are sufficient for our purpose. The mass of the oxygen atom is $2.64 \cdot 10^{-23}$ g, and it follows that one million electron-volts of energy amount to .00107 of one of our units of mass. Now the mass of the electron is .00054; the mass of the proton is that of the H^1 atom less that of its orbital electron, or say 1.0072; the mass of the O^{16} nucleus is that of the O^{16} atom less that of its eight orbital electrons, or say 15.9957. If we make the hypothesis that the O^{16} nucleus is a cluster of sixteen protons and eight electrons, the separate masses of these twenty-four particles add up to 16.1195, and there is a discrepancy of 0.1238 units; but this is perhaps no real discrepancy, but simply the energy which the twenty-four particles yielded up when they gathered into the cluster, and which must be restored to them if they are ever

[9] In the special case of a system of electrified particles acting on one another strictly according to the laws of classical electrodynamics, the equivalence of mass m and energy mc^2 can be derived from these laws; i.e. it can be deduced that two configurations of the system differing in energy by E differ in mass by E/c^2. However, such particles could not form a stable cluster; so that one is compelled to postulate Einstein's general principle, after all.

to disperse again. It amounts to about 115 millions of electron-volts, and this is not an unwelcome figure, for had the value been much smaller we might expect oxygen nuclei to be easily disrupted, which is not the case.

This evidently makes an extra reason for measuring atomic masses with the utmost care: not only are these masses important in themselves as constants of Nature, they may also be used as indices of the stability or the fragility of the various kinds of nuclei. Aston's first apparatus enabled him to measure them to one part in a thousand, an accuracy which may be valuable among the lightest elements but not among the heavier, where the uncertainty rises to one fifth of a unit of mass. His second apparatus proved itself competent to one part in ten thousand, and with its completion in 1925 the second period of isotope-analysis began. Bainbridge in measuring the ratio of He^4 to H^1 pushed onward to a precision severalfold greater, claiming a probable error of only one part in a hundred thousand. With such data as these, it is necessary at times to take account of the fact that what is measured is the ratio of masses of two ions, the unknown and the O^{16} ion; what is tabulated is usually the ratio of the corresponding atoms; but what is required for nuclear theory is the ratio of the masses of the nuclei. Even with contemporary accuracy, though, the correction is still trivial unless the very lightest atoms are involved.[10] It should be mentioned here that band-spectra occasionally permit the ratio of the nuclear masses of two or more isotopes of the same element to be evaluated, with an accuracy which may attain (in the case of the ratio C^{13}/C^{12}) one part in ten thousand.

Not nearly all of the known kinds of atoms have had their masses so precisely measured. Suitable data exist for nearly all of the isotopes of the first ten elements; beyond these there are but twenty-four elements of which even a single kind of atom has been measured, and deplorable gaps between them.

How best to plot these data? This is a difficult problem. Considering the inchoate state of nuclear theory, it would probably be best to plot the measured masses directly, as in Fig. 6—were it not that then the graph would have to be as large as a wall-map. It is

[10] This is due not entirely to the smallness of the electronic mass, but partly to the fact that the ratio of nuclear mass (in standard units) to number-of-orbital-electrons is always between 2 and 3 for all kinds of atoms excepting H^1 for which it is about one.

Aston until 1930 published his estimates of atomic masses coupled not with their probable errors, as the custom is, but with the extreme limits outside of which (in his opinion) the value of the mass in question cannot possibly lie—an unusually conservative policy, because of which some people who have used his values have underestimated their probable accuracy. The ratio of these "uncertainties" to the probable errors is commonly taken, with Aston's concurrence, as three.

much more convenient to plot the differences between each measured mass M and the nearest integer, which latter is the "mass-number" A of the kind of atom in question. Aston prefers to use the quantities $10^4(M - A)/A$, the differences aforesaid divided by the corresponding mass-numbers and "expressed in parts per ten thousand"; these he calls the "packing fractions" in allusion to the principle that elementary particles suffer changes in mass when they are clustered or packed closely together.

If one plots either $(M - A)$ or the packing fraction against A, it is immediately obvious that the values of either do not jump about at random as one progresses along the procession of the atoms in order of atomic mass. The packing fractions lie pretty closely along the sweeping curve in the lower part of Fig. 8, with its odd bifurcation (ordinates on the left!). Not all the available data are represented

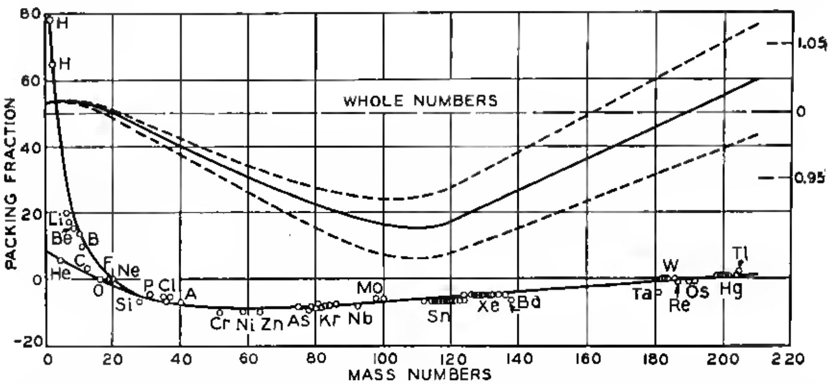

Fig. 8—Deviations of atomic masses from mass-numbers (upper curve) and packing-fractions (lower curve, with points of observation). Curves from the report of a Royal Society discussion of 1929, with subsequent observations filled in from Aston and from Bainbridge.

by dots, as some would fall too close to others to be distinguishable on this scale. The curve of $(M - A)$ is the full curve sketched above (ordinates on the right!).[11]

As the trend of either curve makes clear, the masses of the atoms near either end of the procession, the "light" end and the "heavy" end, exceed their nearest integers; while all through the middle (and

[11] The packing fractions from one end of the curve to the other are mostly uncertain by from one to three units, excepting those of H^1, H^2 and a few other very light atoms. The uncertainty of $(M - A)$ increases steadily with A, as the reader will easily understand; it is indicated by the space between the dashed curves. This is a reason for preferring packing-fraction to $(M - A)$ as a quantity for plotting.

The data omitted in Fig. 8 are: -5 for Cs^{133}, $+2$ for Tl^{203}, -7 for Se^{80}.

by much the largest) part of the procession they fall below their nearest integers. There is a minimum or greatest-negative-value of the difference $(M - A)$ near $A = 110$, and a minimum of the packing-fraction near $A = 60$. It may seem paradoxical that the two minima do not coincide, but the apparent paradox is easily understood.

If all the packing-fractions were negative, and all the atomic masses lay just below their nearest integers, we should infer that all the nuclei consist of particles having one sixteenth the mass of O^{16} when free, and that all the differences $(M - A)$ are losses of mass due to clustering or packing. The policy of plotting packing-fractions is open to criticism because it leads, or rather misleads, to that untenable idea—untenable, because so many of the nuclei show positive values of $(M - A)$. One is obliged to argue that the protons and neutrons which are presumably packed into nuclei undergo an *average* shrinkage in mass from 1.008 or 1.007 to 1.000, and in addition an *extra* change either positive or negative of which $(M - A)/A$ is a sort of a measure. This viewpoint has certain merits, but I think that the best thing to do with a packing-fraction is to retrace the steps whereby it was originally calculated, and thus obtain the mass of the atom in question, which then may be compared with the masses of adjacent atoms, or those of the elementary particles of which one supposes it built, or indeed with anything else whatever.[12]

The sort of reasoning that then is possible can best be shown by illustrations.

We start with H^1, nuclear mass 1.0072, and go ahead to H^2, nuclear mass (by Bainbridge's latest measurement) 2.0131. As $Z = 1$ for this latter nucleus, it might conceivably be either a cluster of two protons and an electron, or a proton and a neutron. Here the principle of the interrelation of mass and energy may prove important: if for either of these models the sum of the masses of the separated particles should be smaller than 2.0131, it would be necessary to discard either that model or the principle. There is no difficulty with the former model, the sum being 2.0149. As for the latter, not even the indirect estimates of the mass of the neutron are sufficiently close to permit the test. One may turn the argument around and deduce that if it is ever shown by other evidence that the H^2 nucleus is a proton plus a neutron, the mass of the latter when free must be more than 1.0058.

Many a search has been made for nuclei of mass-number 3, but all in vain; the non-existence of such kernels may be as significant to the

[12] The same remark goes for the so-called "mass-defect," which for a nucleus of mass-number $4n + b$ (n = any integer, b = any integer less than 4) is computed by adding the masses of n alpha-particles and b protons, and taking the difference between their sum and the actual mass of the nucleus.

theorists of the future as the existence of other kinds. We go on then to the kernel He^4, our indispensable friend the alpha-particle.

The ratios of the masses of the atoms H^1, He^4 and O^{16} are among the most important constants of physics. All are known by now with admirable precision: the three, mutually compatible values 1.0078 : 16 for H^1/O^{16}, 4.0022 : 16 for He^4/O^{16}, and 3.9713 : 1 for He^4/H^1—the two first from Aston, the last from Bainbridge—appear to be uncertain by not more than one place in the last significant figure, if so much as that.[13]

Forming a model for the He^4 nucleus out of four protons and two electrons, we find that not only is it stable by the principle aforesaid, but it is abundantly stable. The difference between Σm the sum of the separate masses and M the mass of the alpha-particle is positive and equal to .029 mass-units, or about twenty-seven million electron-volts! There is consequently no cause for worry over the fact, or rather the appearance, that when alpha-particles with as much as eight million electron-volts of kinetic energy crash into other nuclei, either nothing breaks or else the other nucleus gives way.[14] With the H^2 nucleus the difference $\Sigma m - M$ amounts to less than two million electron-volts, so that we should rather expect it to be broken under similar circumstances.

Mass-number 5 again is missing from the procession, in spite of an ardent and lately-stimulated search.

Mass-numbers 6 and 7 are isotopes of lithium, of which Bainbridge has determined the masses as 6.0145 and 7.0146, with uncertainties of 3 and 6 places in the last significant figure. One can picture the nucleus of Li^6 as a cluster of six protons and three electrons, which have lost altogether 0.033 of a unit of mass or something over thirty million electron-volts in combining. It is more usual, however, to apply a certain very general hypothesis, of which the validity is still quite uncertain: the hypothesis that in every nucleus there are nearly or quite as many completed alpha-particles as the mass will admit. In the case of Li^6 this suggests one alpha-particle, two "loose" protons and one "loose" electron; and about four million electron-volts would have been lost by the three last in attaching themselves to the alpha-

[13] The values and uncertainties as given are: $(1.00778 \pm .00015) : 16$; $(4.00216 \pm .0004) : 16$; and $3.971283 \pm .000042$; the uncertainties being the extreme ones in the first two cases, the probable error in the last (cf. footnote 10).

[14] When protons emerge from a substance bombarded by alpha-particles, why should we assume that they come from the bombarded nuclei and not from the projectiles? Chiefly, I suppose, because in the contrary case they would be expected to appear whatever the substance, whereas actually they vary exceedingly in amount and energy-distribution from one element to another. But there is some reason for thinking that the alpha-particle coalesces with the struck nucleus when the proton comes off, which makes the question rather meaningless.

particle. In the case of Li^7 it suggests one alpha-particle, three loose protons and two loose electrons. This would mean the addition to the Li^6 nucleus of a proton and an electron, originally of total mass 1.0078, which would shrink to 1.000 in process of being added. It seems as though our standard of mass had an objective existence in Li^7, but this is probably misleading.

Lithium can be transmuted by impact either of alpha-particles or of protons. In the former case, neutrons are emitted, together with gamma-rays; in the latter, alpha-particles come off in pairs. What can be inferred about the nuclei?

Here we meet with the great difficulty common to experiments on transmutation: with an element of two or more isotopes, one does not know which is or are being disintegrated. This is sometimes welcome to the theorist, who can ascribe the transmutation to whichever isotope happens best to fit his theory. Thus to explain what happens when protons strike lithium, it is very satisfactory to write:

$$Li^7 + H^1 = 2He^4, \tag{1}$$

a quasi-chemical equation—an equation of nuclear chemistry—in which both masses and charges are balanced, and which implies that the proton and the constituents of the lithium nucleus fuse themselves into a pair of alpha-particles, which kick one another violently apart. Now consider what happens when alpha-particles strike lithium; using n as the symbol for the neutron, we may write either of two of these equations:

$$Li^6 + He^4 = x + n, \qquad Li^7 + He^4 = y + n, \tag{2}$$

in which x would have to stand for a nucleus of atomic number 5—that is to say, a boron nucleus—and mass-number 9, while y would have to stand for a boron nucleus of mass-number 10. Now boron kernels B^{10} are familiar, but kernels B^9 are as yet among the missing; it is therefore much pleasanter to infer that it is the Li^7 isotope which is disintegrated by alpha-particles; and such inferences are often drawn.

Equation (1), as I intimated, should be a balancing of masses as well as of charges; but on putting the measured masses of the nuclei Li^7 and H^1 and He^4 into the equation, one gets 8.020 on one side and 8.004 on the other, and the discrepancy is far beyond the uncertainty of either. This is a very interesting case, because it affords evidence for the principle of the equivalence of energy and mass. According to this principle, we ought to introduce into the equation T_0 the kinetic energy of the particles before, and T_1 the kinetic energy of

the particles after the impact:

$$Li^7 + H^1 + T_0 = 2He^4 + T_1. \qquad (3)$$

It chances that T_1 is considerable, about seventeen million electron-volts (equally divided between the two He^4 nuclei) while T_0 is relatively negligible, since this transmutation can be effected by protons having even less than 10^5 electron-volts of vis viva. Translating T_1 into mass-units we find the right-hand member elevated to 8.018, which agrees within the uncertainty of experiment with the 8.020 on the left. Here is a reaction in which mass has truly been conserved, and there would appear to have been an actual loss thereof, if kinetic energy itself were not possessed of mass.[15]

The emergence of neutrons from proton-bombarded lithium—and beryllium, and boron, not to speak of other elements—is of course the strongest reason for supposing that they exist in these and other nuclei. We can as easily say that the Li^7 nucleus consists of an alpha-particle and a proton and two neutrons, and the alpha-particle of two protons and two neutrons, as we can say that they consist respectively of an alpha-particle and three loose protons and two loose electrons, and of four protons and two electrons respectively. But is there any real difference between the two models? any difference, that is to say, which might be tested by experiment? Or in other words: is there anything to be gained (or lost) by substituting, in a nucleus-model comprising both protons and electrons, a neutron for a proton-and-electron pair? If the mass of a neutron differed considerably (i.e. by a large fraction of a mass-unit) from the sum of those of an electron and a proton, there might be a definite gain (or loss); but this does not appear to be the case. There may however be a really important distinction resulting from the "spins" of these particles, which will be treated in a later instalment.

To return to the procession of the atoms: mass-number 8 is represented by an isotope of beryllium so rare that it has been detected only (possibly not with certainty) in band-spectra. Its nuclear charge and mass-number are such that one may suppose its kernel to be a pair of alpha-particles. It seems obvious to infer that Be^8 is rare, if not non-existent, because two alpha-particles repel one another too violently to hang together. This, however, is a dangerous line of thought, inasmuch as the kernels C^{12} and O^{16} would also be expected

[15] One should strictly define kinetic energy in the relativistic rather than the classical fashion, but the difference is much too small to be observable in these experiments. The test of equation (3) may be regarded by some as merely a new verification of the relativistic dependence of mass on speed so often verified by experiments on electrons, but it seems to me to contain something more.

to consist of nothing but alpha-particles—three and four respectively—and they are among the most stable and abundant varieties which there are. One begins already to guess that nuclear theory is not easy.

Mass-number 9 is represented by the principal isotope of beryllium, mass 9.0155 ± .0006 (Bainbridge). Beryllium is one of the elements which pour out neutrons most lavishly when assailed by alpha-particles, and one would like to infer that the Be^9 nucleus is a cluster of two alpha-particles and a neutron. Formerly the accepted model consisted of two alpha-particles, a loose proton and a loose electron, though this picture made it difficult to understand why beryllium is one of the few light elements which yield up few or no protons when alpha-particles bombard them. On forming the difference of the nuclear masses Be^9 and $2He^4$, we find 1.011, which is a very disconcerting figure, as it is greater than either the accepted value of the mass of the neutron or the sum of those of proton and electron. The excess is very small in each case, so small that without the present-day technique of measurement it would remain undetected; perhaps it is uncertain even yet; but unless and until someone proves that actually there is a deficiency instead of an excess with at least one of the two models, it will be questionable whether the Be^9 nucleus comprises two perfected alpha-particles.

Mass-numbers 10 and 11 are represented by isotopes of boron, masses given by Aston as 10.0135 and 11.0110 with maximum uncertainties of ± .0015. I will use these in explaining how the mass of the neutron is estimated. When bombarded by alpha-particles, boron emits neutrons. Again it is uncertain which isotope emits them; but if we write equations similar to (2), with allowance for kinetic energies:

$$B^{10} + He^4 + T_0 = x + n + T_1; \quad B^{11} + He^4 + T_0 = y + n + T_1, \tag{4}$$

we see that x and y would have to be isotopes of nitrogen, of mass-numbers 13 and 14 respectively. No atom N^{13} is known, but N^{14} is the principal isotope of nitrogen. These facts speak strongly in favor of the second of equations (4), and so does the fact that when nitrogen gas is bombarded by neutrons there are transmutations in which alpha-particles appear—evidently the converse of the process which that equation was first written down to describe.

If now in the second of equations (4) we put the nuclear mass of N^{14} for y, and then insert Aston's values for N^{14} and B^{11} and He^4, we get:

$$\text{mass of neutron} = (1.0051 \pm .005) + (T_0 - T_1). \tag{5}$$

Now in trying to evaluate $(T_0 - T_1)$ one encounters two difficulties which are of no great importance in this case, but may be serious in others. First, the incident alpha-particles do not all have the same speed and the expelled neutrons do not all have the same speed; it may be that $(T_0 - T_1)$ is the same for each individual event, but so long as we can only observe these events in multitudes we have to tolerate a wide distribution of T_0 and a wide distribution of T_1. Second, the kinetic energy of the neutrons is not measured; what is measured is the range of the particles (atom-nuclei) which they strike, and from this the speed of these struck particles is deduced, and from this the kinetic energy of the neutrons themselves, which thus is two steps away from the data! Luckily it is the difference between T_0 and T_1 which enters into the equation, and this is not nearly so large as either; Chadwick estimates it as .0016 mass-unit, so obtaining:

$$\text{mass of neutron} = (1.0067 \pm .005). \tag{6}$$

The alteration seems so much smaller than the uncertainty as to be not worth the making; but the latter again is Aston's extremely generous estimate of the uncertainty, which may be three or four times the probable error; so that perhaps the allowance for $(T_0 - T_1)$ is worth while. Similar computations can be made for the neutrons expelled from Be and Li, but perhaps had better be left for those who have personal acquaintance with the problem of estimating their kinetic energies.[16]

Mass-number 12 is the principal isotope of carbon; it would be the only one known, were it not for observations made on band-spectra of carbon compounds by King and Birge, who detected lines due to C^{13}. This latter nucleus is presumably the residue of the transmutation of B^{10} by the impact of an alpha-particle, which frees a proton and merges with what is left. The process permits another test of the mass-to-energy relation (not so good as the one described above) which I have treated elsewhere.[17]

Mass-numbers 14 and 15 are isotopes of nitrogen, the former being vastly the more abundant.

Mass-numbers 16, 17 and 18 are isotopes of oxygen, the first being much the most abundant. The other two were discovered (by Giauque and Johnston) through observation of faint lines in absorp-

[16] Neutrons are reported to have been expelled from many of the more massive elements by alpha-particle impact. It is interesting to notice that owing to the trend of the packing-fraction curve (Fig. 8) the application of the foregoing reasoning to these neutrons would lead to values of neutron-mass very much closer to 1.000, unless $(T_0 - T_1)$ were to amount to several millions of electron-volts.

[17] *Review of Scientific Instruments*, June, 1933.

tion-bands of oxygen, photographed with the brightest light and the thickest layer of oxygen on earth—the rays of the declining sun, shining obliquely through the air. Aston has since observed them in mass-spectra. They are probably the most unwelcome of all isotopes, since they necessitate an extra precaution in comparing chemical atomic weights with physical measurements of the masses of isotopes. The chemists' unit of atomic weight is one sixteenth the weighted mean of the masses of the oxygen isotopes, while the physicists' unit, as I have said so often, is one-sixteenth-of-O^{16}. The difference between the two, according to the latest estimates of the relative abundances of the three isotopes, is about 125 parts in a million. O^{17} is the presumable residue of the transmutation of N^{14} by impact of an alpha-particle, which frees a proton and fuses with what is left. This is the most completely analyzed of all transmutations, and Blackett, who first observed it in detail by the expansion-chamber method, might be regarded as the discoverer of O^{17}.

Mass-number 19 belongs to fluorine. The mass is given as 19.0000 $\pm$ .002, another remarkable example which might convince one of the objective existence of the unit of atomic mass.

As one goes onward along the list (which space forbids our scrutinizing henceforward in such fullness), one meets a novelty at atomic number 18. Here begin *overlappings* of the atomic masses of different elements: the isotope A^{40} of argon ($Z = 18$) is heavier than K^{39} of potassium ($Z = 19$), and K^{41} is heavier than Ca^{40} ($Z = 20$). The former of these overlappings is responsible for the formerly very surprising "inversion" whereby the chemical atomic weight of argon (39.44) is greater than that of its immediate follower potassium (39.10). Another inversion (involving tellurium and iodine) occurs farther along in the list and is similarly caused, and there are many other overlappings which do not produce so drastic a result.

Mass number 40 is shared by two atoms of different atomic number, different elements therefore, argon and calcium. The reader can pick out other examples from Figs. 6 and 7. There is even an instance of three "isobares," as atoms differing in Z but not in A are called: this is at $A = 124$, the three elements being tellurium, tin and xenon. (There is probably another at $A = 96$, but it is questionable as yet, as of the three in question (Mo^{96}, Zr^{96}, Ru^{96}) the two last are not positively affirmed by Aston.) It will be interesting to find whether measurements of mass can be pushed to such a degree of accuracy as to disclose small differences between isobares. Aston gives 79.926 and 79.941 for Se^{80} and Kr^{80}, but adds "the difference is too near the possible experimental error [one part in 10^4] to be of

much significance." Groups of three or four isobares occur among the radioactive atoms beyond $A = 206$.

Also, as one goes onward along the list, one meets with elements having quite remarkable numbers of isotopes: lead with eight, xenon and mercury with nine, tin with no fewer than eleven put down as certain! At the same time one notices elements of apparently a single isotope only, up almost to the end of the procession; and there is a striking rule, perhaps the most definite yet found in this field: *there is no element of odd atomic number for which more than two stable isotopes are known.* The word *stable* must be inserted, as there are more than two radioactive isotopes for each of the elements 81 and 83. Moreover, for every such element past nitrogen the mass-numbers of the two isotopes (if more than one is known) differ by two units. It was also considered a rule that (past boron) the lighter isotope is the more abundant of the two; but Aston has lately discovered that the contrary is the case with rhenium ($Z = 75$) and thallium ($Z = 81$), so that this rule must be confined to the middle part of the list. This brings us to the question of abundances.

The relative plenty or scarcity of the various elements has been for many years a topic of inquiry among chemists, and also—or even more—among geologists and astrophysicists. It now becomes a subdivision of a larger topic, the relative plenty or scarcity of the various kinds of atoms. Better said, there are now two subjects of research—the relative abundances of the various isotopes within each element, the relative abundances of the elements with respect to one another—and by combining the data of the two one might hope to get the relative amounts of the many kinds of atoms in the whole of Nature.

The latter and older problem, however, is in much the more unsatisfactory state, and seems likely to remain so. We have only the earth's crust, the air, a few meteorites, some nebulæ, and the outermost layers of the stars available for the study; the nebulæ and the stars only by spectroscopic methods, of which the results are not always easy to interpret. The interior of the earth and the interiors of the stars remain impenetrable to us. The relative abundances of the elements in the five more or less accessible regions are by no means the same, and give us no sure basis for guessing what they may be in the inaccessible regions.

Nevertheless, there are rules for the relative abundances of the elements in the earth's crust, which are so strong that one is very much tempted to extend them to the whole of Nature. There is a great predominance of elements of even atomic number over elements of odd (Harkins' rule). There is a predominance of atoms of mass-numbers

divisible by four. There is evident, in Fig. 6, a relative scantiness of atoms for which $(A - Z)$ is, or would be, odd; this would be even more obvious if the dots, instead of being all alike, were proportioned in size to the relative abundances of the isotopes within the elements. It seems unlikely that in the inaccessible parts of the earth and the stars these atoms should be so over-abundant as to restore the balance. Except for this unlikely possibility, we must infer that nuclei for which $(A - Z)$ is odd are not easily formed or else that they break up easily. Such nuclei, if imagined as clusters of protons and electrons, would have odd numbers of electrons; if imagined as clusters of protons and neutrons, they would have odd numbers of neutrons.

In comparing the relative abundances of the different isotopes of a single element, one feels on surer ground. It is a general rule (violated only by the radio-active elements, their end-products, possibly a few others) that these quantities are the same for every sample of a given element, wherever out of the earth's crust *or even out of meteorites* it may have been taken. It looks then as though the mixing of the isotopes within each element had been pretty thoroughly accomplished in the beginning of time, and as though the ratios of their relative amounts might have universal value.

Mostly the ratios are deduced from the darkness of the spots which the isotopes imprint upon mass-spectrum plates. The difficulties of inferring from the aspect of a spot the number of the particles which made it are like those which occur in photography, and are overcome in much the same way. The charges being exactly and the masses nearly the same for the isotopes of a heavy element, one may pretty safely suppose that equal numbers of atoms of such isotopes produce equal effects; but with very light elements this is not so sure. In occasional experiments the total charge which the ionized atoms bring with them is measured, and this is in principle the neater method. It may be carried out acceptably with apparatus not designed for making exceptionally accurate measurements of mass. Bleakney has employed it with hydrogen and neon.

About a couple of hundred abundance-ratios of isotopes in individual elements have now been measured, mostly by Aston. No rule has so far emerged from all these data, excepting the partial one about elements of odd atomic numbers which I cited earlier. There has, however, been a useful and entertaining set of by-products, in the form of revisions of the standard values of the chemical atomic weights. Obviously "physical" values for these can be obtained, if one can measure the masses and the relative abundances of all the isotopes. The highest attainable accuracy of this scheme in the most favorable

cases now somewhat surpasses one part in ten thousand, which is about as good as the chemical methods can offer.

Many of the physical evaluations have been in beautiful agreement with the best-approved of the chemical, reflecting honor on both; but there have been striking temporary exceptions, with ultimate results very surprising to anyone brought up in the tradition that chemical atomic weights stand for the *ne plus ultra* in accuracy. The weights of krypton and xenon were formerly given as 130.2 and 82.9; Aston evaluated them as 83.77 ± 0.02 and 131.27 ± 0.04; within a year (1931) redeterminations of the densities of these gases (perhaps it would be justice to call this a physical rather than a chemical method) resulted in 83.7 and 131.3. Among the elements for which the analysis of isotopes has lately given a value markedly different from the accepted chemical atomic weight, are osmium, selenium, scandium and caesium. It will be interesting to see what happens to these values in the tables of atomic weights.

I left the story of the discovery of H^2 to the end, so as to make earlier mention of several things on which it depended. Apparently it was the joint result of two independent predictions. First, the ratio of the masses of the atoms H^1 and O^{16} agrees remarkably with the ratio of the chemical atomic weights of hydrogen and oxygen: both are certainly between 1.0077 and 1.0078. This agreement seems wonderful testimony to the accuracy of the measurements of physicists and chemists; but it turns out to be a mere coincidence. Such testimony it indeed would be, if H^1 and O^{16} were the sole isotopes of their respective elements; but from the moment when O^{17} and O^{18} were discovered, it could be taken as meaning one thing only (short of actual errors in the work): it could be taken only as meaning that there is an extra isotope (or more than one) of hydrogen, more massive than H^1. This idea came first to Birge and Menzel, who proceeded to compute in what ratio of abundances H^2 and H^1 must stand in order to produce the agreement in question, if H^2 be the only extra isotope. The result must depend, of course, on the ratios of the abundances of O^{17} and O^{18} to that of O^{16}. For these ratios the estimates (made from band-spectra, excepting for a preliminary one by Aston) are not in very good accord. At the time of the prediction of Birge and Menzel, they indicated a ratio of 4500 to 1 for the abundances of H^1 and H^2 in ordinary hydrogen. Second, the diagram of Fig. 6 shows a recurring uniformity, a stepwise pattern, in the broken line connecting the successive dots from $Z = 3$ to $Z = 8$. If isotopes H^2, H^3 and He^5 exist, then this pattern extends uninterrupted down to $Z = 1$.

These were the ideas which brought about the discovery of H^2 by

Urey, Brickwedde and Murphy. At first they did not expect to distinguish such an isotope in ordinary hydrogen; but they inferred from thermodynamical theory that a greater than the normal proportion (of H^1H^2 molecules among the ordinary H^1H^1 molecules) should be obtained by liquefying large quantities of gas and letting it re-evaporate at a low pressure, taking for their investigation the last two or three cubic centimetres of liquid out of several thousand. It turned out later that they could detect H^2, or "deuterium" as they have named it, in ordinary hydrogen; but in these special samples the evidence of it was far more patent.

This evidence is the advent of "shifted lines" in the ordinary line-spectrum of atomic hydrogen. The frequencies of atomic spectrum-lines depend on the ratio of the masses of electron and nucleus, in a manner which in times past has been of the utmost value in establishing the present-day model of the atom [18]; the difference between the values of this ratio for H^1 and H^2 is only that between 1/1850 and 1/3700, and results in a frequency-difference of less than three parts in ten thousand, and yet the corresponding wave-length-difference is easy to detect with spectroscopes. The existence of H^2 entails that each of the familiar spectrum-lines of H^1 should be attended by a faint companion, displaced by this percentage toward lesser wave-lengths. Urey, Brickwedde and Murphy observed the faint companions of the four most prominent of the Balmer lines; others have since observed them, and just before these pages started for the press, there appeared the photographs [19] taken by Ballard and White of four lines of the Lyman series with their companions, which I reproduce as Fig. 9.

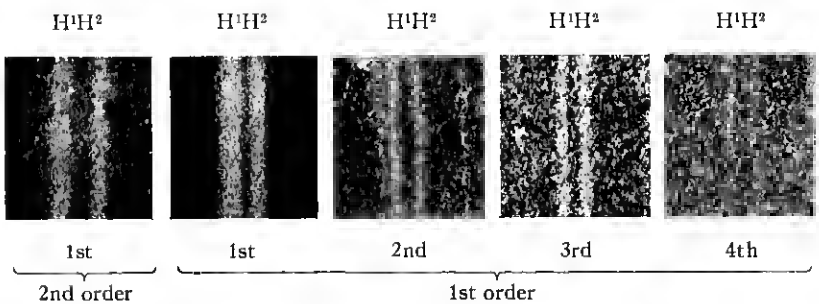

Fig. 9—Lines of the Lyman series of ordinary hydrogen (H^1) accompanied by the corresponding lines of H^2. The first picture on the left shows the first line of the series, photographed in second order; the others show the first four lines of the series from left to right, photographed in first order. (S. S. Ballard & H. E. White; *Physical Review.*)

[18] Cf. the ninth of this series of articles (October, 1925), or my *Introduction to Contemporary Physics*, pp. 308–312.

[19] I am indebted to Messrs. Ballard and White for sending me the original of this picture.

It will be noticed that in these photographs the lines of each pair are of approximately equal brightness; whereas in the original work of Urey, Brickwedde and Murphy, the one due to H^2 was always by far the fainter. The gain is due to the fact that G. N. Lewis has discovered an amazingly potent method for separating H^2 from H^1, of which the efficiency outruns by far anything that was formerly hoped for or dreamed of; it is said that samples of hydrogen or of hydrogen compounds may be obtained, in which the heavier isotope exceeds the lighter by more than one hundred to one! This appears to be a god-send to the chemists, as there is reason to suspect that the properties of "heavy" hydrogen and of its compounds may be markedly and even fantastically different from those of "light" hydrogen and *its* compounds; a whole new province of chemistry seems to be opened to explorers. Here, however, we are concerned only with the mass of the nucleus; and in the original samples there was sufficiently much of H^2, to permit of its mass being measured by Bainbridge with the result and with the accuracy which I have quoted already. As for the question of the relative abundance of H^2 and H^1 in "ordinary" hydrogen, it is now in a quite unsatisfactory state; for various experiments give various results, mostly disagreeing with the prediction which had a share in the discovery.